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Pit Realization Process Manufacturing Readiness Assessments

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August 27, 2019

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List of Acronyms

AB	Authorization Basis
CER	Complete Engineering Release
AER	Advance Engineering Release
CQER	Conditional Qualification Evaluation Release
DA	Design Agency
DEV	Development Phase
DOP	Detailed Operating Procedure
DPBPS	Defense Programs Business Process System
EE	Engineering Evaluation
EER	Engineering Evaluation Release
FMEA	Failure Modes and Effects Analysis
FPU	First Production Unit
F&OR	Functional and Operating Requirements
IPG	Integrated Phase Gate
LANL	Los Alamos National Laboratory
MCMS	Manufacturing Capability Maturity Scale
MRL	Manufacturing Readiness Level
NNSA	National Nuclear Security Administration
PA	Production Agency
PTRL	Process Technology Readiness Level
PPI	Process Prove-In Phase
PRR	Production Readiness Review
PRP	Product Realization Process
PRT	Product Realization Team
QER	Qualification Evaluation Release
QUAL	Qualification Phase
RAMI	Reliability, Availability, Maintainability, and Inspectability
SON	Statement of Need
TRL	Technology Readiness Level
TSR	Technical Specifications and Requirements
WR	War Reserve

Reviews in Order of Occurrence

SRER	Scope and Requirement Exchange Review
PFSGR	Product Feasibility Study Gate Review
PCSGR	Product Cost Study Gate Review
CRR	Component Requirement Review
CDR	Conceptual Design Review
PCDGR	Product Conceptual Design Gate Review
BDR	Baseline Design Review
PPEGR	Product Pre-Production Engineering Gate Review
PDDR	Product Definition and Documentation Review
FDR	Final Design Review
PPPGR	Pre-Pilot Production Gate Review
PRR	Production Readiness Review

I. INTRODUCTION

This document defines a manufacturing readiness assessment process within a Product Realization Process (PRP) for pit manufacturing at Los Alamos National Laboratory (LANL) having the following objectives.

- Meet National Nuclear Security Administration (NNSA) Defense Programs Business Process System (DPBPS) PRP requirements.
- Use language established within LANL's pit manufacturing program.
- Enable a disciplined approach to evaluate pit manufacturing readiness.
- Provide effective tools and metrics to assess manufacturing system maturity.

Numerous studies in both private industry and the federal government have found that insertion of immature manufacturing processes increases risk and cost which significantly decreases the probability of program success. LANL's pit manufacturing readiness assessments (Manufacturing Readiness Level (MRL), Process Technology Readiness Level (PTRL), Producibility Assessment, and Manufacturing Capability Maturity Scale (MCMS)) have been developed to support a high probability for success as processes mature toward production. Manufacturing readiness relies on a complex relationship of production equipment, personnel, facilities, and other factors that comprise a manufacturing system. The four assessments and their evaluation against targets reduce risks in maturing the many attributes of a manufacturing system illustrated in Figure 1.

Figure 1, Pit Manufacturing System

This document provides objectives, exit criteria (targets) and description of activities for each of the four assessments at each MRL. The nine MRLs are summarized in Section IV and defined in Appendix A. The document expands on the manufacturing assessments defined in DPBPS documentation (C017, Conduct MRL Assessment) which directs the Production Agency (PA) for a

major component in a weapon system to review the MRL criteria for completeness and add criteria as needed (CR37253). Additions to DPPBS criteria presented in this document are intended to provide effective pit manufacturing specific metrics to assess LANL's manufacturing system maturity. To emphasize the technical readiness (capability) of the pit manufacturing processes, a PA PTRL assessment is defined in this document with the expected levels given in the associated MRL level. The LANL PTRL addresses plutonium manufacturing processes which include a combination of the manufacturing equipment (technology) and the plutonium containment structure surrounding and interacting with the equipment. LANL's PTRL assessment is not to be confused with the Design Agency (DA) product specific Technology Readiness Level (TRL) assessment (C018) of a pit which leads, by TRL 9, to a pit shown to meet all Department of Defense functional requirements. For a new pit design or a pit with limited changes from a current design, the DA product specific required activities advancing the TRL levels defined in C018 are documented in the DA Pit Certification Plan. The third assessment related to MRL levels is the DPBPS Producibility Assessment (C048) which is used to assign NNSA Producibility Codes. Producibility is assessed at certain MRL levels during product realization against expected targets in manufacturing maturity (e.g., yield, cost, cycle time, units/time). The fourth assessment in this document is the MCMS assessment defined in DPBPS and used to identify which products or processes in early development stages carry higher risk and may take longer to mature.

II. BACKGROUND

When compared to most development and manufacturing efforts within the Nuclear Weapons Complex and commercial industry, the costs and risks associated with implementing immature technology, immature manufacturing processes, or immature product designs into pit manufacturing processes are significantly higher. Operating costs, authorization basis requirements, product costs, and the unique nature of plutonium introduce cost and risk not typically experienced elsewhere. The purpose of MRL/PTRL/Producibility/MCMS assessments is to provide a rigorous system engineering framework supporting technology development, process development, and pit manufacturing maturation to reduce risk associated with these efforts.

The assessments are a required part of DPBPS product realization supporting the development, implementation and qualification of a particular weapon system or of a major system component such as the pit. The assessments in this document meet and expand on the DPBPS Product Realization (R001) requirements and the other DPBPS documents presented below as applied to pit manufacturing. R001 (FR89482) directs the Product Realization Team (PRT) to use an Integrated Phase Gate (IPG) approach defined by an IPG Implementation Plan (T140). During each stage in product realization given in the next section, R001 (FR29561) directs the PRT to conduct PA led MRL assessments and DA led TRL assessments at each MRL/TRL level. C017 includes the following activities in an MRL assessment.

- Define MRL targets (exit criteria) in the PRT Qualification Plan (T076).
- Assess and assign a product MRL.
- Compare the MRL assignment with the target and identify gaps.

In addition, C017 requires Producibility and Manufacturing Capability Maturity to be assessed at appropriate MRL levels. LANL pit MRL levels within DPBPS against generic pit realization schedules for each phase are given in the next section. Each pit PRP is somewhat unique and the PRT and Project Team (program management team) for a particular pit may tailor activities and

schedules somewhat differently from the generic schedules given in this document, while still meeting DPBPS requirements.

For Plutonium Facility operations at LANL, the use of MRL and related assessments support process implementation and help reduce risk in the following ways.

- The assessments will be used to determine where further work is needed to advance new processing technologies or equipment maturity to mitigate risk.
- The assessments will be integrated with the Plutonium Facility lifecycle process to ensure that efficient, safe, and robust equipment is deployed to the manufacturing floor.
- For processes requiring significant development, Process Implementation Teams are formed which operate under a development and implementation plan and which includes a maturation plan showing the expected rate at which they will advance within the readiness levels.

III. INTEGRATION OF MRLS WITH DPBPS AND A PIT REALIZATION PROGRAM

Five product readiness phases are used by LANL and LLNL as part of the Product Realization Process for a pit. The relation of the following phases to the PRP Stages and MRLs is given in this section.

- Concept Assessment Phase (MRL 1)
- Feasibility, Cost and Conceptual Design Phase (MRL 2-3)
- Process and Specification Development (DEV) Phase (MRL 4-5)
- Process Prove-In (PPI) Phase (MRL 6-7)
- Product Qualification (QUAL) Phase (MRL 8)

The Feasibility, Cost and Conceptual Design phase completes technology selection and ensures sufficient maturity of specifications and processes to support the DEV Phase. The DEV Phase modifies (or installs if necessary) required production processes and then develops the processes and control parameters so that the product being produced will fully meet the DA design definition early in the PPI Phase (Transition PPI[1], MRL 6 targets).

The PPI Phase (MRL 7 targets) establishes WR product quality of the manufacturing facilities, production processes, inspection and acceptance methods, material, and personnel so that the pits being produced will support successful completion of the QUAL Phase. PPI Phase activities include any process adjustments and corrective actions needed before qualification and production begin. By the end of the PPI Phase, the PA and DA have verified that all the elements of the manufacturing system shown in Figure 1 are inherently capable of yielding War Reserve (WR) quality products to cost and schedule in the QUAL Phase.

At the end of PPI the PRT must conduct a Production Readiness Review (PRR) to demonstrate readiness for qualification builds before entering the QUAL Phase. In the QUAL Phase the PRT must finalize any Engineering Evaluations (EEs) not completed in the PPI Phase per T046. The Qualification Plan defines whether EE activities are performed on product

[1] The laboratories define PPI to include both MRL 6 and MRL 7. DPBPS R001 has the PPP Gate Review performed after MRL 6. The PPP Gate Review marks the start of Manufacturing Prove-In (MRL 7). The term Process Prove-In is first used in the definition of MRL 7. MRL 6 (Manufacturing System Integration) is a transitional MRL where the CER is published and Engineering Evaluations (EEs) begin, but also where final development activities are completed and pit builds demonstrate that all requirements are being met. This document uses the terms Transition PPI builds during MRL 6 and Final PPI builds during MRL 7.

manufactured during the PPI Phase or during the QUAL Phase, giving flexibility to which product builds are used in performing the EE activities. EE builds can begin in the PPI Phase following the Complete Engineering Release (CER). The QUAL Phase achieves WR qualified manufacturing capable of yielding diamond stamped pits and achieves final producibility targets. The QUAL Phase ends with the diamond stamping of the First Production Unit (FPU).

The following sections give the alignment of PRP Stages and MRL levels within each of the phases using a generic DPBPS product realization schedule and give the goals and criteria for each phase.

III.A. Feasibility, Cost and Conceptual Design Phase

The PRP Feasibility, Cost and Conceptual Design Stages (matching DPBPS Phase) follow an initial Concept Assessment Stage. The following reviews (and associated DPBPS requirements) per R001 occur within these stages.

- (FR48522) Scope and Requirement Exchange Review (SRER) (MRL 1)
- (FR11562) Product Feasibility Study (PFS) Gate Review
- (FR22869) Product Cost Study (PCS) Gate Review (MRL 2)
- (FR49193) Component Requirement Review (CRR)
- (FR68947) Conceptual Design Review (CDR)
- (FR31422) Product Conceptual Design (PCD) Gate Review (MRL 3)

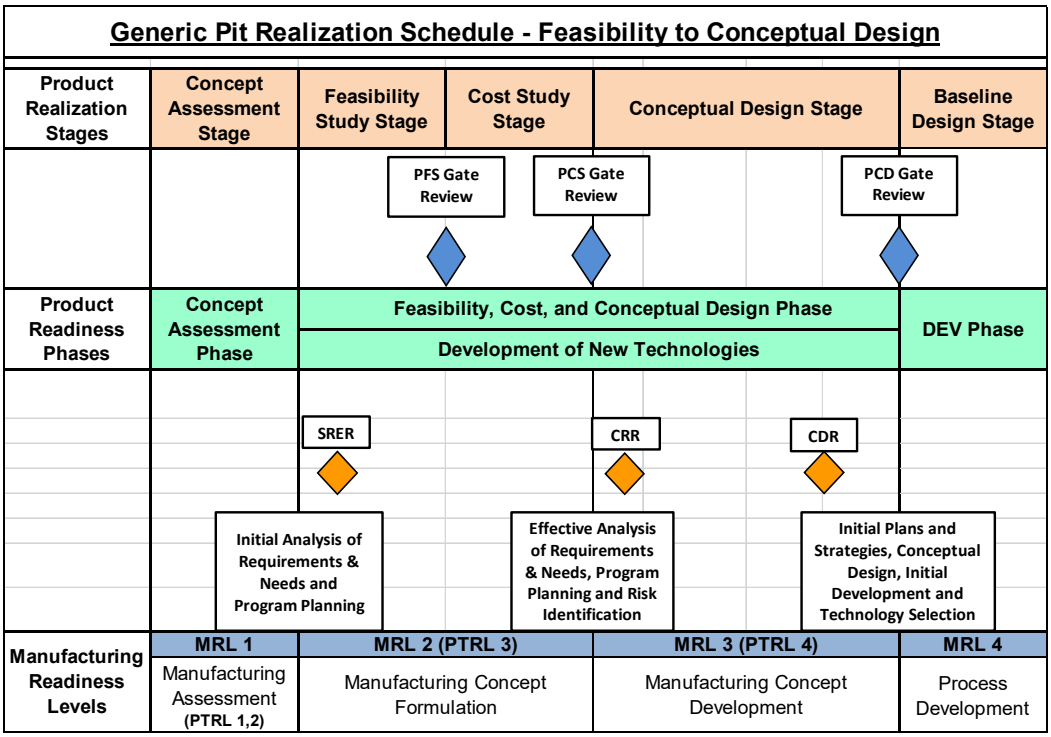

Figure 2, Schedule and Objectives for the Feasibility, Cost and Conceptual Design Phase

The goal of the Feasibility Stage and Cost Study Stage is to ensure sufficient maturity of program information, product requirements, schedule, and cost estimates against the proposed design to support a decision to progress to the Conceptual Design Stage which represents the start of engineering development. The goal of the Conceptual Design Stage shown in Figure 2 is

to complete technology selection and to ensure sufficient maturity of specifications and processes to support the Baseline Design Stage (the start of the DEV Phase).

The following criteria define completion of the Feasibility, Cost and Conceptual Design Phase.

- Updated plans for certification, qualification, production and surveillance strategies.
- Updated pit physical and functional requirements documentation.
- Updated technology and manufacturing maturity assessments.
- Documentation of lifecycle schedule, costs, and risks.
- Completion of the conceptual design for the pit.
- Initial development and technology/process selection.
- Advance Engineering Release (AER) authorizing procurement of long-lead items.

III.B. DEV Phase and Transition PPI Phase (MRL 6)

The DEV Phase and Transition PPI Phase follow the PRP Concept Design Stage and cover the PRP Baseline Design Stage and initial part of the Production Engineering Stage which ends with the Pre-Pilot Production Gate Review. The goal of these phases is to bring processes and specifications to a point where product definition is finalized, a Complete Engineering Release (CER) is achieved, and pit builds are meeting specifications with an acceptable producibility. The following reviews (and associated DPBPS requirements in R001) occur in these phases.

- (FR72797) Baseline Design Review (BDR)
- (FR85817) Product Pre-Production Engineering (PPE) Gate Review (MRL 4)
- (FR51855) Product Definition and Documentation Review (PDDR)
- (FR91203) Final Design Review (FDR) (MRL 5 completion follows this review)
- (FR87842) Pre-Pilot Production (PPP) Gate Review (MRL 6)

The goal of the DEV Phase shown in Figure 3 is to complete manufacturing development and builds to meet the following objectives.

- LANL will establish all necessary facilities, equipment, specialized tools and procedures to manufacture pit components and assemblies. Processes are meeting an initial producibility rating of C by the end of MRL 4.
- The project will support DA activities necessary to review, integrate, and finalize designs and specifications. The formal exchange of information and decisions is documented and released through the engineering authorization system.
- The project will complete manufacturing capability development activities required to establish the processes and parameters that will be used to manufacture the required components and assemblies.
- Technology and manufacturing reviews will be conducted to establish, document and communicate levels of maturity, and to enable a disciplined approach in evaluating, identifying and addressing needs, gaps and risks in achieving planning targets throughout the life of the project.
- At the end of the DEV Phase assembled pits are being manufactured that meet product definition sufficient to support the following activities in the Transition PPI Phase.
    - Releasing all CERs.
    - Final development so that manufactured pits meet all specifications.
    - Engineering Evaluations and DA pit certification tests during MRL 6.

The following two criteria define completion of the DEV Phase.

- Completion of the PPE Gate Review (MRL 4, the end of the Baseline Design Stage).
- Issue the final design.
- Compete MRL 5 process development and demonstration required to support finalizing product definition for the FDR and required to support MRL 6 activities.

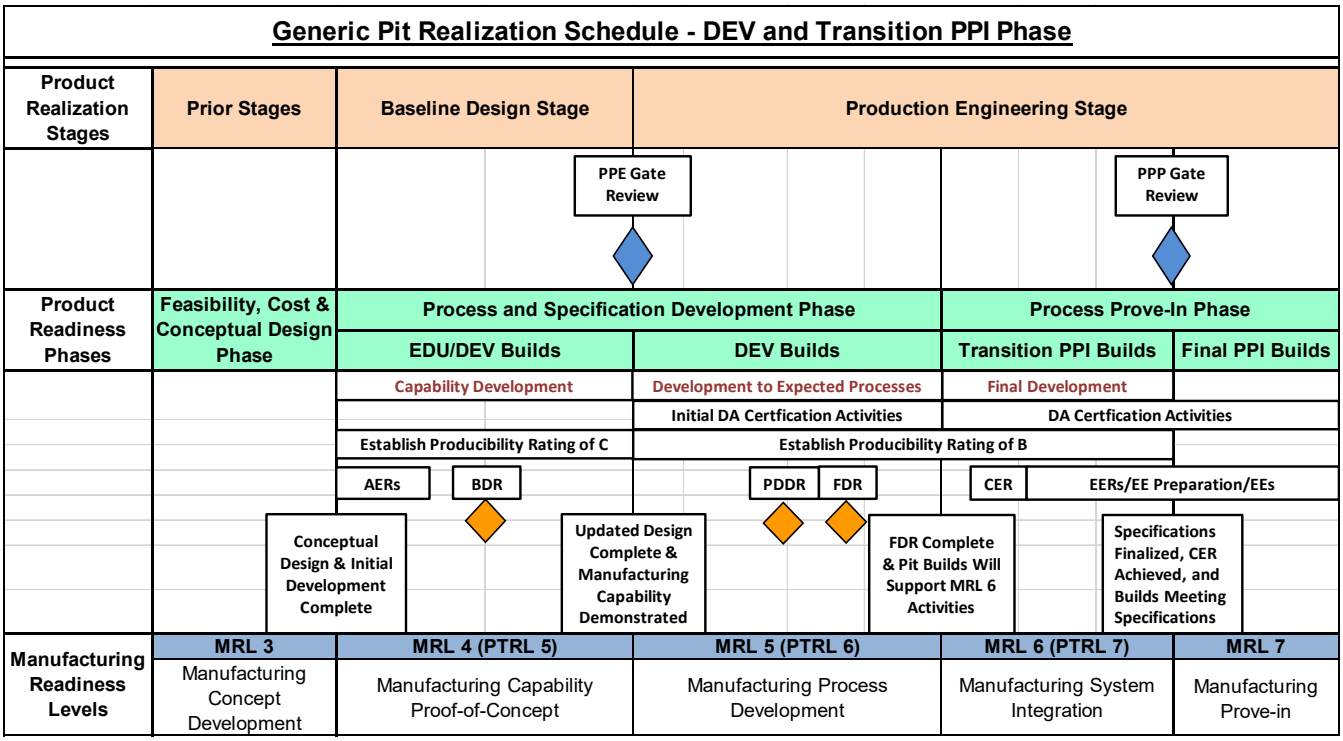

Figure 3, Schedule and Objectives for the DEV Phase and Transition PPI Phase

The goal of the Transition PPI Phase shown in Figure 3 for manufacturing process development and capability is to meet the following objectives.

- Manufacturing processes are producing pits using expected production processes by manufacturing and inspection personnel in an operational environment.
- Manufactured pits, using WR certified non-nuclear components and subassemblies, meet final released product definition.
- Builds at LANL and its supply chain are meeting an interim producibility rating of B.
- Facilities and equipment upgrades have been completed as required to allow initial Engineering Evaluations to be performed.

The following criteria defines completion of the Transition PPI Phase.

- Produce a series of PPI builds that accomplishes the following:
  - Complete final specification changes and the CER.
  - Complete final development demonstrating that processes meet all specifications.
  - Demonstrate that pit builds are meeting MRL 6 exit criteria requirements.
- Finalize plans and strategies for certification, qualification, and production.

III.C. Final PPI Phase and QUAL Phase

Final PPI Phase and QUAL Phase shown in Figure 4 complete the Production Engineering Stage. The following review occurs per R001 with completion of MRL 7 (completion of the PPI phase).

- (FR93135) Production Readiness Review (PRR)
- (FR45026) When the product is rated less than MRL 7 in the PRR, the PRT must obtain approval from the FPM for the path forward.

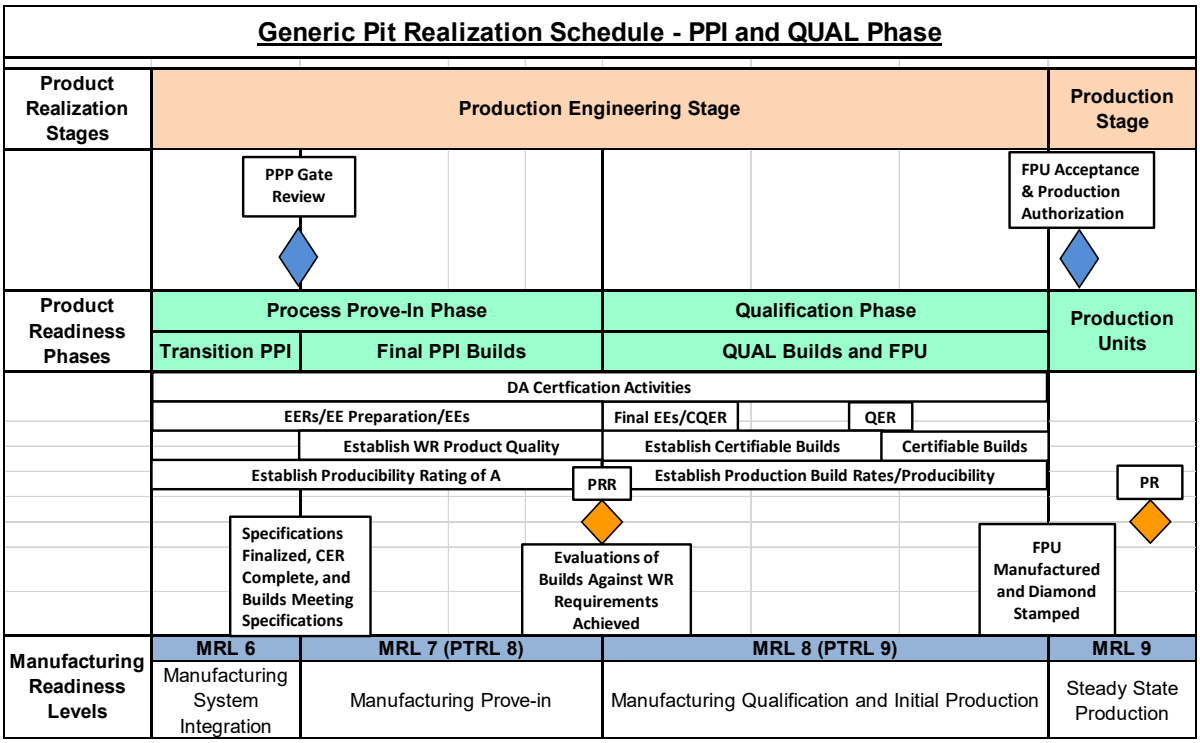

Figure 4, Schedule and Objectives for the Final PPI Phase and QUAL Phase

The goal of the Final PPI phase shown in Figure 4 is to achieve a manufacturing level that produces pits meeting the following objectives.

- Verify that all elements of the manufacturing system are capable of yielding mark quality products to cost, schedule, and quality performance goals before starting qualification for production.
- Verify that manufacturing facilities, production processes, tooling, test equipment, inspection processes, acceptance methods, material, and personnel have reached production readiness.
- Complete process adjustments and corrective actions before qualification begins.

The following criteria defines completion of the PPI phase.

- Complete and document that manufacturing qualification status is at a level that provides for the evaluation of builds in the QUAL phase.
- Builds at LANL and its supply chain are meeting a producibility rating of A.

The goal of the QUAL phase shown in Figure 4 is to produce pits meeting the following objectives.

- Complete any remaining EEs and publish a Conditional Qualification Evaluation Release (QER) for manufactured pits.
- Build a designated number of pits that meet product definition and submit applicable documentation to NNSA for concurrence that the builds could be accepted as WR pits.
- Release the Final QER.
- Establish build rates meeting producibility targets for the start of production and supporting final DA certification tests.
- Complete DA certification tests and manufacture the First Production Unit.

Successful completion of MRL 8 and the QUAL Phase is achieved with acceptance (Diamond Stamping) of the First Production Unit. Steady State Production (MRL 9) begins with NNSA Production Authorization.

IV. PIT MANUFACTURING READINESS LEVELS

MRLs are used to measure the maturity of evolving manufacturing systems with respect to product realization phases. The MRL assignment is a snapshot of where the maturity of the manufacturing system is at a given point of time. It is the highest MRL level for which all exit criteria are satisfied. For pit manufacturing, the process transitions from development using prototype equipment and surrogate metals to development with operational production processes using plutonium occurs earlier than the basic DPBPS MRLs, requiring alignment of the process transitions with development and build requirements for the DEV, PPI and QUAL phases and with build requirements for DA certification. The exit criteria and description of activities for the MRLs are defined in Appendix A. The MRL maturity of the overall manufacturing system assignment is the lowest MRL for an individual process within the system. The nine MRLs are summarized as follows.

- MRL 1 Manufacturing Assessment
  Early collaboration with multidisciplinary concept team to identify design; process; materials; and manufacturing options, needs, and risks.
- MRL 2 Manufacturing Concept Formulation
  Options, gaps, and risks identified and evaluated. Scope, production strategy, and requirements are exchanged.
- MRL 3 Manufacturing Concept Development
  Initial manufacturing options down-selected. Manufacturing development needs and strategies identified. Costs are estimated for the program. Conceptual Design Review completed.
- MRL 4 Manufacturing Capability Proof-of-Concept
  Manufacturing system capability development complete and producing component/subsystem/pit proof-of concept development builds. Baseline Design Review completed.
- MRL 5 Manufacturing Process Development
  Product Definition and Documentation Review and Final Design Review completed. Non-nuclear components and subassemblies are meeting design specification. Pit builds meet product definition sufficient to support activities in the MRL 6 stage.

- MRL 6 Manufacturing System Integration
  Pit builds are successfully meeting requirements. Processes, materials, tooling, personnel skills, inspection and test equipment have been demonstrated and approved. Formal procedures completed to ensure quality and production planning systems are in place.
- MRL 7 Manufacturing Prove-In
  Builds are meeting WR quality based on Engineering Evaluations and LANL PA assessment. Successful producibility achieved. All suppliers/materials are available and qualified.
- MRL 8 Manufacturing Qualification and Initial Production
  Manufacturing of certifiable pits is established and the First Production Unit is accepted (Diamond Stamped). Initial production metrics are achieved.
- MRL 9 Steady State Production
  The ability to consistently meet cost, quality and schedule targets is achieved.

Exit criteria and description of activities are defined in Appendix A for each of the nine MRL levels. The MRL levels include the following attributes.

- Product Design/Definition
- Process Capability/Control
- Process Quality Elements
- Facility/Staff/Equipment
- Tooling/Test Equipment
- Manufacturing System / Other

V. PIT PROCESS TECHNOLOGY READINESS LEVELS

Due to the costs and risks associated with installing, testing, operating, and maintaining equipment in the Plutonium Facility manufacturing line, LANL defines and uses the Process Technical Readiness Levels given in Appendix B to focus on the technical readiness of process equipment as part of evaluating MRLs. The PTRLs address plutonium pit manufacturing processes, which are different from most components in a weapon system which match the DPBPS MRL definitions more closely. Plutonium Facility processes include a combination of the manufacturing equipment (technology) and the plutonium containment structure surrounding and interacting with the equipment, technical readiness levels for these integrated processes also includes authorization basis requirements, technical safety requirements, facility operating requirements, and RAMI (reliability, availability, maintainability, and inspectability) requirements. The PTRLs use the following environment and equipment definitions.

- Laboratory environment – testing of laboratory equipment is performed either in cold environment using surrogates or in a plutonium facility using laboratory configured equipment.
- Relevant environment – testing of prototype equipment is performed in an environment which simulates operational conditions in the Plutonium Facility. Depending on equipment function, a relevant environment could simply be in air or could include testing with plutonium in an environmentally controlled glovebox.
- Operational environment – testing of prototype or final equipment in the manufacturing line with the intent of qualifying the equipment to WR requirements.
- Production environment – final qualified manufacturing processes are being used in the manufacturing of qualification builds and WR production.

The PTRL assignment for an individual process provides a snapshot of the technical maturity of the manufacturing process at a given point in time. It is the highest PTRL level for which all exit criteria are satisfied for a process. The PTRL level required at each MRL level is given as an exit criteria in the corresponding MRL. The exit criteria and description of activities for the PTRLs are defined in Appendix B. The PTRL maturity of the overall manufacturing system assignment is the lowest PTRL for an individual process within the system.

The nine PTRLs are summarized as follows.

- PTRL 1 Concept Formulated
  Invention begins, practical application basic scientific principles is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.
- PTRL 2 Concept Demonstrated
  Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction.
- PTRL 3 Key Elements Demonstrated in Lab Environment
  Low fidelity (or laboratory) equipment is built and operated in a laboratory environment.
- PTRL 4 Prototype Process Demonstrated in Relevant Environment
  Prototype process built and operated in a test environment to demonstrate overall performance with realistic support elements that demonstrates performance in critical areas.
- PTRL 5 Representative Process Demonstrated in Relevant or Operational Environment
  Prototype development equipment operated in relevant or operational environment. Note: If prototype equipment is to be installed in the Plutonium Facility, cold testing and demonstration is required to verify that the equipment meets applicable Technical Safety Requirement (TSR), Functional and Operating Requirements (F&OR), and all Authorization Basis (AB) requirements.
- PTRL 6 Process Demonstrated in the Production Facility
  Prototype production or production equipment is operated in the Plutonium Facility. DEV components or materials are produced using this equipment. If prototype equipment does not meet specified reliability, availability, maintainability and inspectability (RAMI) requirements, equipment progression is suspended until issues are resolved.
- PTRL 7 Process Qualified Through Test & Demonstration
  Prototype equipment meets PPI build and RAMI requirements and has become production equipment. Production equipment is operated in the Plutonium Facility to produce initial PPI builds completing final development and supporting Complete Engineering Releases.
- PTRL 8 Manufacturing System Capability Finalized
  Production equipment is operated in the Plutonium Facility to produce final PPI builds for DA qualification (Engineering Evaluations) and Production Agency qualification.
- PTRL 9 Operational Use of Deliverable
  Production equipment is operated in the Plutonium Facility to produce QUAL builds verifying WR manufacturing capability. FPU is completed and WR qualified allowing production to begin.

VI. PIT MANUFACTURING PRODUCIBILITY ASSESSMENTS

Producibility addresses the relative yield, cycle times, costs and risks of options in product designs, manufacturing processes, production and support systems, and tooling. The producibility assessment focuses on the process manufacturing capability attribute of the MRL. Producibility

should be assessed throughout product development to ascertain readiness before making commitments to production.

Producibility assessments are used to accomplish the following.

- Enable a disciplined approach to evaluate the relative ease of manufacturing products.
- Provide metrics (e.g., yield, cycle time, units/time) and an assessment of manufacturing capability maturity, cost, and the ability to meet the required production rate on schedule.
- Provide input for making key decisions, for example, pursing parallel path manufacturing options.

Producibility codes given in Appendix C are used to measure the maturity of evolving manufacturing capabilities with respect to product realization. It is important to establish a producibility basis in MRL 4. When products are assigned a code of D, E, or I, the PRT shall document actions to improve producibility. Producibility may be reassessed at any time if the key conditions from the previous assessment have changed.

As was discussed for PTRLs, plutonium processes transition to operational production processes earlier than the basic DPBPS MRLs. The advancement of producibility is also accelerated for a pit PRP. At the end of PPI (MRL-7, PTRL-8) processes are manufacturing pits to WR product quality (based on Engineering Evaluations and LANL PA assessment) that are cost effective, repeatable, and well characterized. Producibility Code A describes this level of production. What is cost effective and repeatable (rejection rates) for Code A are production targets set by the PRT and program management for the end of PPI. In the Qualification Phase the manufacturing of certifiable pits is established (based on LANL Area Office assessment) and the program should be brought to the initial targets for production (production rates/rejection rates/cost).

Producibility is assessed at the following MRL levels.

- MRL 4 – Producibility rating of C has been achieved.
- MRL 6 – Producibility rating of B has been achieved.
- MRL 7 – Producibility rating of A has been achieved.
- MRL 8 –Builds at the PA and its supply chain have successfully met programmatic targets for production.

VII. PIT MANUFACTURING CAPABILITY MATURITY SCALE

The MCMS levels defined in C017, and given in Appendix D, were created to identify which processes in an early development program carry higher risk and may take longer to mature since MRLs do not indicate at what rate technologies mature. In addition, differentiation between MRLs is minimal during early development. The criteria are very basic (five levels with colors) which highlights the maturity (risk level) of processes in the manufacturing flowsheet. The MCMSs are used at MRLs 1-3 and initially in the Baseline Design Stage as an assessment of development risks to make decisions on the choice of processes. For an NNSA Pit Realization Program, a more formal risk assessment takes over during the Baseline Design Stage.

VIII. Appendix A – Manufacturing Readiness Level Criteria

Level	Name	Attributes	Exit Criteria	Description of Activities
1	Manufacturing Assessment	**Product Design/Definition**	Rough production quantities/rates defined.	Early collaboration occurs between production and design engineers. Strategic planning and assessments are performed with respect to needs and capabilities (technology, facilities, material options, waste/recycling, etc). High level risks including product, business, safety, storage, hazardous materials and security are identified.
		Process Capability/Control	No specified exit criteria.	
		Process Quality Elements	No specified exit criteria.	
		Facility/Staff/Equipment	Capacity/Capability Assessments initiated.	
		Tooling/Test Equipment	No specified exit criteria.	
		Manufacturing System / Other	□ Production Strategy initiated. □ Initial Risks (product, business, safety, security) documented.	
2	Manufacturing Concept Formulation	**Product Design/Definition**	□ Scope and Requirements Exchange has occurred. □ Pit Qualification Strategy developed. □ Initial System Conceptual Design and Requirements developed.	Production Strategy continues to be refined and covers criteria that would affect cost and risk. Production (process & product) qualification strategies are also developed. Manufacturing technology options explored with respect to existing equipment; materials; and facilities; and gaps are identified (storage, cleaning methods, material handling, utility ventilation capacity, etc.). Virtual simulation and evaluations may be performed for process capability with respect to the conceptual design. Cost estimates are rough order of magnitude. High level risks (including product, business, safety and security) are further assessed and updated. An initial System Conceptual Design is completed, including a Manufacturing Assessment.
		Process Capability/Control	□ ROM process cost estimates available. □ Manufacturing technology options identified, assessed and documented. □ Manufacturing Assessment performed using an initial System Conceptual Design, scope, requirements, and implementation strategy. □ Manufacturing processes at PTRL 3 or higher.	
		Process Quality Elements	□ Manufacturing Qualification Strategy developed.	
		Facility/Staff/Equipment	□ Facilities and equipment gaps and budget needs documented. □ Infrastructure capacity/capability assessments drafted.	
		Tooling/Test Equipment	No specified exit criteria.	
		Manufacturing System / Other	□ Production Strategy updated (including waste stream disposition paths & material reprocessing concepts identified). □ Risks updated.	
3	Manufacturing Concept Development	**Product Design/Definition**	□ Conceptual Design Review complete and verified to meet customer requirements. □ Requirement Reviews completed.	Primary technology down-select decisions are performed including waste processing technologies. Production strategies are being refined with details of sourcing options, selected methods, and process development areas identified (cost/performance tradeoffs occurring). Test Equipment strategy and plan is determined and should include plan(s) for inspection development and planning for reference/qualification units. Product qualification planning begins. Conceptual Design Review is complete for components and sub systems and the design is verified to meet customer requirements. Key manufacturing processes are acquired (or built) and operated in a laboratory environment.
		Process Capability/Control	□ High level process flow maps completed. □ Technology down-select decisions documented with supporting test performance. □ Cost estimates documented. □ Development procedures/travelers drafted. □ Production Control planning completed. □ Process capacity/capability assessments drafted. □ Process PTRL 4 Assessment of all major processes completed.	
		Process Quality Elements	□ Draft PRT Qualification Plan created. □ Initial process quality requirements defined.	
		Facility/Staff/Equipment	Infrastructure capacity/capability assessments updated.	
		Tooling/Test Equipment	□ Tooling strategy and plan developed. □ Prototype tooling design initiated. □ Inspection strategy and plan developed.	
		Manufacturing System / Other	Production Strategy updated. Initial Make/Buy Assumptions documented.	

Level	Name	Attributes	Exit Criteria	Description of Activities
4	Manufacturing Capability Demonstration	**Product Design/Definition**	□ Baseline product definition released (i.e., drawings, models, product specification, etc.). □ Baseline Design Review complete and verified to meet customer requirements. □ Development Engineering Release (DERs) -- on critical subsystems and components. □ AERs authorizing required long lead procurement released. □ Product definition updated and released for FDR.	Significant design/requirement changes are occurring and interfaces are being identified. Critical product features are identified. Product definition is sufficiently detailed and released such that a production strategy can be finalized and MRL 5 activities can begin. Material down-select decisions made. Facilities and equipment upgrades are in progress. Design for X (Manufacturability, Testability, etc.) and informal producibility have been assessed. Tooling needs are identified with prototype tooling being evaluated/updated. Engineering and production staffing assessments are performed. Procedures are being drafted an approved. Advanced Engineering Release (AER) authorization for long lead procurement is in place. Development pit builds have occurred at the Production Agency. Prototype equipment is operated in a relevant manufacturing environment (i.e. inert atmosphere, corrosives, etc) to demonstrate performance in critical areas (which usually includes evaluation of equipment performance using surrogate materials or plutonium).
		Process Capability/Control	□ Key process areas identified. □ Process PTRL 5 assessment of processes completed. □ Development builds of nuclear and non-nuclear components and subassemblies have occurred. □ Assembled pits demonstrating manufacturing capabillity are being built. □ Producibility rating of C has been established.	
		Process Quality Elements	□ Process quality requirements and deliverables defined. □ PRT Qualification Plan (including EE plan) updated and released.	
		Facility/Staff/Equipment	□ Facility and operational requirements developed. DOPs approved for development equipment. □ Facility and equipment upgrades are defined and authorized. □ Engineering and production staffing assessments have been performed and documented. □ Training requirements identified.	
		Tooling/Test Equipment	□ Prototype tooling orders/fabrication initiated. □ Critical prototype tooling fabricated. □ Tooling and test equipment Baseline Design Review complete. □ Inspection processes are available and calibrated for development activities.	
		Manufacturing System / Other	□ Production Strategy finalized. □ Development procedures/travelers approved and available. □ Risk Assessment revised. □ Non-nuclear component/subassembly Hardware Plan released in time to meet development requirements.	
5	Manufacturing Process Development	**Product Design/Definition**	□ Product Definition and Documentation Review (PDDR) complete. □ Final Design Review (FDR) is complete. □ Product definition updated if required by the FDR.	Design/requirement changes may occur and interfaces are not yet fully defined. Product definition is maturing (i.e., acceptance tests, equipment, sequences, and conditions are determined; only limits are being finalized). The product definition (drawings, models, product specification, etc.) is updated as needed based on the FDR and released to the PA. Manufacturing processes, equipment and materials are evaluated and characterized. Detailed process maps are documented. Process operating parameters and controls are established. Quality requirements are informally validated. Informal, hands-on training of manufacturing personnel is occurring. The manufacturing system is in place for development activities. Builds at the production agency and its supply chain are occurring. The Final Design Review is completed. A detailed qualification plan has been released. Equipment is installed and tested as a system in an operational manufacturing environment. This corresponds to evaluation of full-scale prototype or production equipment performance and operability under realistic operational conditions including glove box containment. Equipment produces parts using plutonium. Proposed design changes to the prototype or planned changes to the production system are documented and approved for installation in the production facility.
		Process Capability/Control	□ Detailed Process Maps Finalized. □ Producibility targets set (acceptable vs. unacceptable reject rates defined) and initial assessment completed. □ Critical Manufacturing Parameters (CMPs) documented. □ Configuration management in place. □ Builds of non-nuclear components and subassemblies are meeting design specification. □ Process PTRL 6 assessment of processes. □ Assembled pits are being manufactured that meet product definition sufficient to support activities in the MRL 6 stage including initial pit certification tests.	
		Process Quality Elements	□ Draft PA WR Quality Plan released. □ MRL 6 and MRL 7 quality requirements set. □ Software Qualification Plans released. □ Procurement QA requirements for equipment and materials defined for the PPI phase. □ Final PRT Qualification Plan (including EE plan) released.	
		Facility/Staff/Equipment	□ Capacity/capability assessments updated. □ Engineering review confirming that equipment upgrades will meet facility and operational requirements. □ Equipment, process and facility upgrades have been initiated and critical upgrades complete.	
		Tooling/Test Equipment	□ All development tooling available. □ Tooling and test equipment Final Design Review complete. □ Inspection processes qualified to support MRL 6.	
		Manufacturing System / Other	□ Procedures and travelers updated and available. □ Risk Assessment updated.	

Level	Name	Attributes	Exit Criteria	Description of Activities
6	Manufacturing System Integration	**Product Design/Definition**	□ Product definition released to the PA with no TBDs. □ Baseline definition finalized with Complete Engineering Releases (CER).	Engineering design/requirement changes should significantly decrease (impact & quantity) and interfaces should be clearly defined. Product definition baseline is complete (i.e., no TBDs exist) and released to the PA. Component/Subassembly drawings, procedures, detailed process maps, bill of materials, schedules and other data required by the supply chain and manufacturing systems are complete and available for use. Formal training of manufacturing personnel occurs. Development builds at the PA and its suppliers meet product definition. Production equipment is installed and brought to operational status in the production facility. Performance is evaluated against product and operational requirements. Test plans for demonstration and qualification are developed and approved. Final changes to production systems are documented and approved.
		Process Capability/Control	□ Builds at the PA and its supply chain are meeting an interim rejection rate target. □ Process PTRL 7 assessment of processes. □ Assembled pits meeting all released product definition are being manufactured. □ Producibility rating of B has been established.	
		Process Quality Elements	□ Final PA WR Quality Plan released.	
		Facility/Staff/Equipment	□ Product is built to requirements using expected production processes by manufacturing and inspection personnel. □ Facilities and equipment upgrades are complete and updated DOPs approved. □ Equipment and software qualified for MRL 7 activities. □ Maintenance procedures are complete.	
		Tooling/Test Equipment	□ Calibration procedures complete for inspection processes. □ Inspection equipment calibrated and results documented with accuracy statement. □ Production tooling released and available. □ Long term requirements for tooling maintanence and replacement identified and appropriate orders placed.	
		Manufacturing System / Other	□ Final controlled procedures and travelers meeting PPI process qualification requirements are approved and released. □ Initial Production Planning System complete and under version control.	
7	Manufacturing Prove-in	**Product Design/Definition**	□ Successful Production Readiness Review completed.	Product definition is stable. Demand is driven by the production planning system and materials are purchased from approved suppliers. Product meets definition requirements. Characterized processes are integrated and proven-in and process controls are in place. Stable production metrics and procedures have been defined. Non-nuclear components process qualification and manufacturing approval activities are completed. Manufacturing personnel (including inspectors) are trained and qualified as required. WR product quality is established (based on EEs and PA assessment). Safety basis is approved. Facility process qualification and approval activities are conducted where required. Manufacturing demonstration ends with the completion of Process Prove-In (PPI).
		Process Capability/Control	□ Builds at the PA and its supply chain are meeting rejection rate targets at a level to establish production metrics required by the end of MRL 8. □ Producibility rating of A has been established. □ Capacity/capability/reliability assessments finalized. □ Process PTRL 8 assessment of processes. □ Engineering Evaluations are complete. □ Metrics defined for "Steady State Production". □ All Conditional QERs released.	
		Process Quality Elements	No specified exit criteria.	
		Facility/Staff/Equipment	□ Operator/inspector training and qualification activities complete.	
		Tooling/Test Equipment	□ QERs released for inspection processes.	
		Manufacturing System / Other	□ Pits meeting specification are being manufactured to WR product quality requirements.	

Level	Name	Attributes	Exit Criteria	Description of Activities
8	Manufacturing Qualification and Initial Production	**Product Design/Definition**	□ Final pit Qualification Engineering Release (QER) accepted.	Characterized and controlled processes are proven to be production ready. Quality and production metrics are assessed. Production process definition is verified against the qualification plan. Final DA review of manufacturing and inspection processes completed. Manufacturing of certifiable pits is established (based on LANL NNSA Area Office assessment) and final QER released. Ability to meet cost targets and production schedules is demonstrated. Acceptance of First Production Unit is completed.
		Process Capability/Control	□ Initial steady state production metrics achieved. □ Processes qualified for WR production. □ Process PTRL 9 assessment of processes completed.	
		Process Quality Elements	□ Quality Assurance Inspection Procedure (QAIP) released if required for FPU acceptance.	
		Facility/Staff/Equipment	No specified exit criteria.	
		Tooling/Test Equipment	No specified exit criteria.	
		Manufacturing System / Other	□ First Production Unit (FPU) is accepted. □ Any Preproduction-Start findings closed.	
9	Steady State Production	**Product Design/Definition**	□ Successful Production Review complete.	Product definition, procedures and manufacturing & inspection systems are mature, proven, and in a maintenance mode. The design is stable (few deviations/changes), processes are stable (high producibility), quality is acceptable and stable and there is a demonstrated capability to meet customer requirements at cost and on schedule. Production is at rate quantities and has achieved stable production metrics. Significant process control data is becoming available for process improvements. Production tooling is released with adequate capacity. A stable, qualified supplier base exists. Quality metrics exist to monitor trends and improvement activities. A Production Review occurs approximately one year into production (where required).
		Process Capability/Control	□ Stable Production metrics are achieved and maintained.	
		Process Quality Elements	No specified exit criteria.	
		Facility/Staff/Equipment	No specified exit criteria.	
		Tooling/Test Equipment	No specified exit criteria.	
		Manufacturing System / Other	No specified exit criteria.	

IX. Appendix B – Process Technology Readiness Level Criteria

Level	Name	Objective	Exit Criteria	Description of Activities
1	Concept Formulated	Invention begins, practical application basic scientific principles is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Documented description of the application/concept that addresses the feasibility and benefit of the technology.	Practical applications are beginning to be invented or identified. Applications are still speculative and there is no proof or detailed analysis to support assumptions. Examples might include applied research in a field of potential interest.
2	Concept Demonstrated	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction.	Documented analytical/experimental results validating predictions of key parameters. Approved test plan and acceptance criteria for PTRL 3 testing.	Active research and development is initiated. This includes analytical and laboratory-based studies to physically validate analytical predictions of key elements of the technology. These studies and experiments should constitute "proof-of-concept" validation of the applications/concepts formulated at PTRL 1. Examples include the study of separate elements of the technology that are not yet integrated or representative.
3	Key Elements Demonstrated in Lab Environment	Low fidelity (or laboratory) equipment is built and operated in a laboratory environment.	Approved SON. Approved TSR. Documented and approved definition of relevant environment. Sufficient laboratory demonstration and documentation of test performance to support authorizing process engineering and installation of a prototype system in PTRL 4. Approved test plan and acceptance criteria for PTRL 4 testing.	The key process elements must be integrated to establish that the pieces will work together. The validation should be consistent with the requirements to meet intended applications, but it is relatively low-fidelity when compared to a final process. Laboratory development of hardware and software system components demonstrated to perform as an integrated process is completed.
4	Prototype Process Demonstrated in Relevant Environment	Prototype process built and operated in a test environment to demonstrate overall performance with realistic support elements that demonstrates performance in critical areas.	Documented test performance demonstrating agreement with analytical predictions and TSR. F&ORs are developed and approved. FMEA and RAMI requirements developed and approved. Statements of Need released. Relevant environments defined. Approved test plan and acceptance criteria for PTRL 5 testing.	Fidelity of the process increases significantly. Key elements are integrated with realistic supporting elements so that the process can be tested and demonstrated in simulated or actual environments.
5	Representative Process Demonstrated in a Relevant or Operational Environment	Prototype development equipment operated in a relevant or operational environment. Note: If prototype equipment is to be installed in PF-4, cold testing and demonstration that the equipment meets applicable TSR, F&OR, and all AB requirements is required.	Equipment produces EDU parts using surrogates or plutonium. Prototype must must meet TSR and F&ORs. RAMI concepts of prototype are demonstrated. Proposed design changes to the prototype or planned changes to the production system documented and approved. Completed report verifying that Pit Manufacturing Capability has been demonstrated. Approved test plan and acceptance criteria for PTRL 6 testing.	Represents a major step in a technology's demonstrated readiness, which includes testing a prototype process in a high-fidelity relevant or actual environment.

Level	Name	Objective	Exit Criteria	Description of Activities
6	Process Demonstrated in the Production Facility	Prototype production or production processes are operated in PF-4. DEV pits are produced using this equipment. If any prototype processes do not meet specified RAMI requirements, process progression is suspended until issues are resolved.	The processes are producing DEV pits in an operational environment using plutonium. All DOPs are approved. Test plan for demonstration and/or qualification is developed and approved. Any remaining changes to production systems are documented and approved. Completed report documenting that manufacturing processes will support MRL 6 activities. Approved test plan and acceptance criteria for PTRL 7 testing.	Processes are at or near their planned operational level. This represents a significant step beyond PTRL 5 and requires the demonstration of development versions of pits being manufactured in in PF-4. Activities include integration and demonstration of the manufacturing processes over the entire manufacturing flowsheet.
7	Process Qualified Through Test & Demonstration	Prototype equipment meets PPI build and RAMI requirements and has become production equipment. Production equipment is operated in PF-4 to produce initial PPI builds completing final development and supporting Complete Engineering Releases.	All processes have demonstrated the ability to produce parts meeting all specifications and facility/operating requirements. Completed report documenting that the manufacturing system meets all requirements to support MRL 7 Engineering Evaluations and LANL process qualification.	The processes have been proven to work in their final form under expected conditions. In almost all cases, this PTRL represents the end of system development and includes test and evaluation of manufactured pits to validate that the manufacturing system is meeting design specifications.
8	Manufacturing System Capability Finalized	Production equipment is operated in PF-4 to produce final PPI builds for DA qualification (Engineering Evaluations) and Production Agency qualification.	Production equipment configuration and procedures are finalized and under WR quality control. The manufacturing system is demonstrated and documented to be capable of producing pits meeting WR requirements and meeting facility/operating requirements.	All manufacturing processes been proven and qualified in their final form under expected conditions. This PTRL represents the end of manufacturing system implementation. However, final DA pit certification activities in MRL 8 may lead to some level of process refinement.
9	Operational Use of Deliverable	Production equipment is operated in PF-4 to produce QUAL builds verifying WR manufacturing capability. FPU is completed and WR qualified allowing production to begin.	All processes are part of a pit manufacturing system that meets WR requirements, manufacturing requirements and facility requirements. NNSA documentation that QUAL pit builds have become WR certifiable is released. The FPU is WR certified by NNSA. WR production is authorized.	All process are operating in their final form and under expected operational conditions. Some process modification or use of a newly developed process may be implemented after WR pit production has started. Such a process would have its own process realization schedule.

X. Appendix C – NNSA Producibility Codes

Code	Description
A	Employs preferred processes, acceptance/inspection testing and/or equipment that are cost effective, repeatable, well characterized, and produce/test quality product. Commitment to quantity production of product that meets design intent can be achieved with low risk to schedule requirements.
B	Requires acquisition and/or characterization of processes, inspection/acceptance testing, and/or equipment that are new to the plant but established elsewhere and obtainable. Commitment to quantity production of product that meets design intent can be achieved with moderate risk to schedule requirements. Costs, repeatability and/or characterization are acceptable but not optimized.
C	Requires new or modified processes, inspection/acceptance testing, and/or equipment acquisition that are obtainable within pre-production activity. Commitment to quantity production of product that meets design intent can be achieved with acceptable risk to schedule requirements. Costs, repeatability and/or characterization are marginally acceptable and not optimized.
D	Requires new or modified processes, inspection/acceptance testing, and/or equipment. Available processes and/or equipment are not acceptable for quantity production with regard to schedule performance, yield, quality, reliability, or cost. Improvement in producibility is required.
E	Requires processes, inspection/acceptance testing, and/or equipment that do not exist and may not be achievable. Commitment to support WR product performance, cost, or schedule requirements represents unacceptably high risk.
I	Adequate design criteria are not available to permit assessment of producibility. Assessment of commitment to support WR product performance, cost, or schedule requirements is not yet possible.

XI. Appendix D – Manufacturing Capability Maturity Scale

MCMS Level	Maturity	Criteria
1	**Very High**	**Manufacturing: Standard process** Exists with no or only minor modifications being required. Engineering design and upgrade is adequate.
2	**High**	**Manufacturing: Minor process modification** Requires new development well within the experience base. A single development approach is adequate.
3	**Moderate**	**Manufacturing: Need improved process / equipment** Requires new development but similarity to existing experience in most critical areas is sufficient. Dual approaches recommended for those outside existing experience.
4	**Low**	**Manufacturing: New process / equipment** Requires new development but similarity to existing experience is sufficient in only a subset of critical areas. Dual development approaches should be pursued.
5	**Very Low**	**Manufacturing: Process does not exist** Requires new development outside of any existing experience base. No viable approaches exist that can be pursued with any degree of confidence.